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By

T. E. Bunch

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SOME CHARACTERISTICS OF SELECTED MINERALS FROM CRATERS

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Shock metamorphism of natural rocks results in a variety of deformational microstructures. The most important observations obtained from detailed optical studies of selected minerals from meteorite craters and from cryptoexplosion structures are as follows: (1) the most striking feature of shocked quartz from Meteor Crater, Wabar, and Holleford and in several specimens from Clearwater Lakes, Kentland, Middlesboro, and the Ries Structures is the apparently instantaneous brittle fracturing with very little movement of shattered grains; (2) the degree of cleavage development and the texture of the shattered quartz is different from that in quartz deformed by other geologic processes; (3) deformation lamellae parallel to the basal plane (0001) of quartz are present in several of the specimens examined; (4) multiple sets of planar features in quartz are unique to meteorite and cryptoexplosion craters: the forms $\omega\{10\bar{1}3\}$ and $\pi\{10\bar{1}2\}$ are normally rare in quartz but are quite distinctive in quartz from impact and cryptoexplosion craters and may be useful criteria for shock deformation; (5) the development of numerous kink bands and deformation bands in quartz from the above structures is common; such structures may be rarely found in quartz deformed under ordinary geologic stresses and strain rates; (6) numerous deformation bands, kink bands, complex deformation twins, and brittle fractures are common in associated feldspars; (7) micas are intricately kinked. Most of these microstructures are readily distinguished from those in tectonites.

INTRODUCTION

G. K. Gilbert was one of the first eminent scientists to speculate about the origin of lunar craters. He strongly suggested, in his treatise on the moon (Gilbert, 1893), that the lunar craters were produced by meteorite impact, but he later argued against a meteorite impact origin for Meteor Crater, Arizona. Many years elapsed following Gilbert's provocative ideas, during which time geologic thought progressed rapidly, but little attention was paid to the possible geological aspects of meteorite impact. Then in 1936, Boon and Albritton postulated a mechanism which they considered to be feasible for producing the so-called cryptovolcanic structures by meteorite impact. Since that time a continuing controversy has been waged concerning the origin of terrestrial explosion craters (*i.e.*, structures which are morphologically similar to Meteor Crater) and cryptoexplosion structures. Dietz (1959, 1960) proposed the neutral term "cryptoexplosion" structure in place of "cryptovolcanic" to better describe the circular disrupted structures earlier interpreted by Bucher (1936) to be of volcanic origin. Bucher (1963) and other workers favor an intraterrestrial energy source (volcanic explosions or rapid gaseous release) for such structures, while Dietz (1963) and others favor an extraterrestrial source (meteorite or comet impact). Probably the only point of agreement in this controversy is that most of the structures have originated by violent explosion.

Coes (1953) succeeded in synthesizing a high pressure (20–40 kb) polymorph of SiO_2 which was later called coesite. There was considerable doubt that this high pressure phase could be found in near-surface rocks of the earth because of the high pressures needed for its formation. A breakthrough for the meteorite impact proponents came when Chao *et al.* (1961) isolated coesite from highly-deformed Coconino Sandstone of Meteor Crater, Arizona. Coesite has subsequently been found in quartz-bearing rocks at Wabar, Saudi Arabia; the Ries, Germany; Bosumtwi, Ghana; Holleford, Canada; Kentland, Indiana; and Lake Mien, Sweden. However, the presence of coesite has not been universally accepted as

evidence of meteorite impact (Bucher, 1963). Stishov and Popova (1961) succeeded in making a very high pressure modification of SiO_2, isostructural with rutile, which has a density of 4.28 g/cc. This form, later named stishovite, was found naturally in rocks from Meteor Crater and the Ries, Germany (Chao *et al.*, 1962; Chao and Littler, 1963). The pressures required for the quartz-to-stishovite transformation are in excess of 80 kb (Sclar *et al.*, 1962).

Dietz (1947, 1959, 1960) suggested that unusual conical fractures called shatter cones were unique to cryptoexplosion craters and were the result of the shock associated with meteorite impact. Shatter cones have been found in many cryptoexplosion structures in the United States and Canada, as well as in the Steinheim, Germany and Vredefort, South Africa structures. They have not been found, thus far, in meteorite craters containing preserved meteorites.

The presence of coesite or stishovite, shatter cones, and meteorite fragments associated with geologic structures of questionable origin are used to support the meteorite impact theory. It is unfortunate, however, that coesite and stishovite are metastable and may not persist for long periods of time. Many of the cryptoexplosion structures contain little or no quartz-bearing material and the search for high-pressure SiO_2 polymorphs is thus very difficult. Meteorite fragments soon weather and are lost as evidence. Shatter cones may be possibly produced by static loading (Bucher, 1963), and are not yet accepted as definitive criteria for an impact origin.

The true test for any postulated origin lies in the rocks themselves. If these anomalous structures are truly meteorite craters formed by rapidly applied pressures and supergeologic temperatures, then the rocks and their constituent minerals should show unique signs of the catastrophic event. Actually, at the time the work reported here was undertaken, very few mineralogical and petrological investigations had been made, although McIntyre (1962) had examined several surface specimens from the Clearwater Lakes structures, Canada, and concluded that they were "shock" metamorphosed by meteorite impact.

Clearly, "a good hard look" at the constituent rocks and minerals of these highly debated structures is needed to establish definitive criteria for any origin. This need was strongly suggested by Bucher (1963, p. 693), who wrote:

"Before we look to the sky to solve our problems miraculously in one blow, we should consider the possibility that cryptoexplosion structures and explosion craters may hold important clues to processes going on at great depth below our feet, even if it threatens to lead us back to another traditional concept, that of cooling of the outer mantle. Distrust in traditional thinking should not deter us from looking hard at all aspects of the problem."

and by Dietz (1963, p. 663), who countered by writing:

"I concur with Bucher that traditional thinking should not be overlooked; we should not forego the mundane in favor of the esoteric. On the other hand, meteoritic impacts must play a geologic role, and the cryptoexplosion structures seem to be examples. On the status of astroblemes I believe we stand today where we stood in 1930 relative to the acceptance of the Barringer Crater (Meteor Crater) as a bona fide meteorite crater, following the writing of Barringer, Rogers, Spencer, and Blackwelder. The case is not yet proven but the scales are tipped in its direction."

The present article is concerned mainly with the description and geologic implications of deformational microstructures commonly observed in rocks from several of these controversial geologic structures, from one well-known meteorite impact crater (Meteor Crater), and from one nuclear explosion crater (Sedan Nuclear Crater). The scope of this article does not allow a complete description of all the unique consequences of shock found in the rocks studied; however, several other associated shock features (high-pressure polymorphs, shock-fused glass, and shock-disordered quartz and feldspar) are mentioned.

Specimens were examined from two generally-accepted meteorite impact craters; Meteor (Barringer) Crater, Arizona, and Wabar, Arabia. Specimens were also obtained from a number of cryptoexplosion structures, including Kentland,

Indiana; Manson, Iowa; Middlesboro, Kentucky; Clearwater Lakes, Quebec; Holleford, Quebec; Lac Couture, Quebec; Manicouagan, Quebec; the Ries, Germany; and Vredefort, South Africa.

TERMINOLOGY AND CRYSTALLOGRAPHIC NOTATION

Deformation lamellae are narrow, closely-spaced subplanar features having slightly different refractive indices and birefringence from the host material. They originate as slip planes containing arrays of piled-up dislocations. A deformation lamella can be recognized under phase contrast illumination as a narrow (1μ or less) linear trace that is asymmetric, being dark on one side (higher refractive index) of the discontinuity and light (lower refractive index) on the other (Christie, Griggs, and Carter, 1964; Carter *et al.*, 1964; Carter, *this vol.*, p. 453). *Planar features* are rather sharp discontinuities that resemble both fractures and deformation lamellae. They are parallel to rational and/or irrational crystallographic planes and may possibly represent "annealed" deformation lamellae that have separated upon release of locked-in strain. *Deformation bands* are planar structures that contain material having slightly different crystallographic orientation than that of the host grain. *Slip planes* are commonly inclined at high angles to deformation bands and slip in adjacent bands may differ in degree and direction. *Kink bands* are deformation bands bounded by surfaces of band gliding which cut across the active glide planes. As a result of deformation, material within the kink band has rotated with respect to material outside the band. The axis of external rotation of the bent lattice lies in the slip plane normal to the slip direction (Turner *et al.*, 1954). *Deformation twinning* or *mechanical twinning* is a process by which atoms move into new positions by homogeneous shear parallel to the composition plane; parts on either side of the composition plane are mirror reflections of each other.

The term *explosion crater* is used here as a general term to denote craterlike structures that were formed by violent disruption; it is not meant to imply any particular genetic origin (man-made, volcanic, or impact). *Shock disordering* (*structural*), *shock isotropization*, and *shock vitrification* are synonymous terms used to signify a solid state transformation of crystalline material to a vitreous or glassy state by strong shock.

The nomenclature of quartz crystallographic planes used in this paper is:

r–positive rhombohedra	$\{10\bar{1}1\}$
z–negative rhombohedra	$\{01\bar{1}1\}$
m–unit prism	$\{10\bar{1}0\}$
a–second order prism	$\{11\bar{2}0\}$
c–basal pinacoid	$\{0001\}$
ξ–second order trigonal pyramid	$\{11\bar{2}2\}$
s–second order trigonal dipyramid	$\{11\bar{2}1\}$
x–trigonal trapezohedron	$\{51\bar{6}1\}$
ω–rhombohedra	$\{10\bar{1}3\}$
π–rhombohedra	$\{10\bar{1}2\}$

DEFORMATION TEXTURES AND OPTICAL PROPERTIES OF QUARTZ

Natural quartz has an ultimate compressive strength of ~20 kb and is one of the strongest common minerals. The strength of quartz is increased under confining pressure to such a degree that quartz has never been rendered ductile by high confining pressure at room temperature (25°C). Christie, Heard, and La Mori (1964), by experimental deformation of quartz, attempted to produce plastic deformation by applying confining pressures equivalent to those at depths of 100 km in the earth's crust. Their specimens failed by rupture along "faults" that were crystallographically oriented, and the authors suggest that faulting was initiated by small amounts of slip on planes parallel to c, r and z, m and a. The experiments demonstrated that extensive plastic deformation of quartz does not occur under conditions of high confining pressure (27–30 kb) at room temperature. They further suggest that the resultant textures might be similar to deformed quartz at meteorite impact sites. In recent experiments at high pressures (15–20 kb) and moderate temperatures (400°–800°C) Christie and his co-workers (personal communication, March, 1965) have produced fractures that developed parallel to deformation

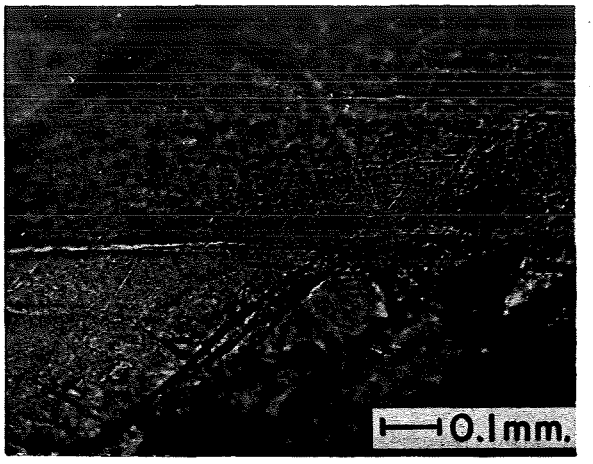

Fig. 1. Photomicrograph of quartz grain (West Clearwater Lake), showing faulting parallel to the basal plane (E-W-trending) and r (N-E-trending). Grain tilted on universal stage. Plane-polarized light.

lamellae. The majority of the lamellae are parallel to c, r, z, ξ, and ξ'.

Many unusual textures (microstructures) occur in quartz from meteorite craters and cryptoexplosion structures. McIntyre (1962) was one of the first to recognize abnormal deformation structures in natural quartz that had presumably been shocked by meteorite impact. Since that time much experimental evidence has been made available for evaluating the behavior of quartz under high confining or shock pressures. In this section a description and discussion of new evidence from detailed studies of microstructures in quartz from known and suspected meteorite impact sites is presented.

A. Brittle Fracture

Deformation stresses may bring about the failure of quartz by plastic flow (slip) or by brittle fracture. Brittle fracture commonly results from quenching through the alpha-beta transition temperature or from rapid loading. Stresses in the rock would develop from shock waves derived from hypervelocity impact. Studies of shock effects from experimental deformation of solids under impulsive loading (Duvall, 1963) showed that at some sufficiently high value of shock pressure, atomic bonds in a solid are not able to sustain the high stresses; the material either fractures or yields plastically, depending on the temperatures involved.

In many of the rock samples studied, quartz and its host rocks were completely shattered; no evaluation of crystallographic control could be made. Cleavage fractures with shear faulting and plastic deformation were reported from the Holleford structure (Bunch and Cohen, 1963). The deformation texture was described as being similar to that in quartz deformed experimentally at high confining pressure. Highly fractured quartz from Clearwater Lakes shows fair crystallographic control. The most common cleavages developed are parallel to c, r, and z, and m and a. In a few specimens a substantial amount of faulting has occurred either during or after fracturing (Fig. 1). Christie, Heard, and La Mori (1964) and Carter (*this vol.*, p. 453) have suggested the crystallographically controlled faulting in quartz may be a reliable indicator of intense shock.

Quartz grains in coesite-bearing Coconino Sandstone from Meteor Crater are highly fractured with little development of cataclastic texture. Bunch and Cohen (1964) reported prominent cleavage in quartz from Meteor Crater. A total of 1958 observations of cleavage fractures in newly acquired samples of shocked Coconino Sandstone from the center of the crater and from throughout zones on the rim were made on grains selected at random. Of these observations, 35 percent are cleavage planes parallel to r or z (Fig. 2). Other cleavage planes observed, in order of decreasing abundance are c (26 percent), ξ (11 percent), m or a (8 percent), ω (4 percent), s (3 percent), and π (2 percent). Undetermined planar fractures total 11 percent. The extinction pattern of quartz under crossed nicols is extremely mottled and may indicate microfracturing or limited plastic flow. Several large fractures that appear to have irrational indices are actually combinations of several cleavage planes. These results agree favorably with those given earlier by Bunch and Cohen (1964).

Very little evidence of plastic deformation was noticed in ten different thin sections and several thousand quartz grains of Coconino Sandstone. A few deformation lamellae parallel to the basal

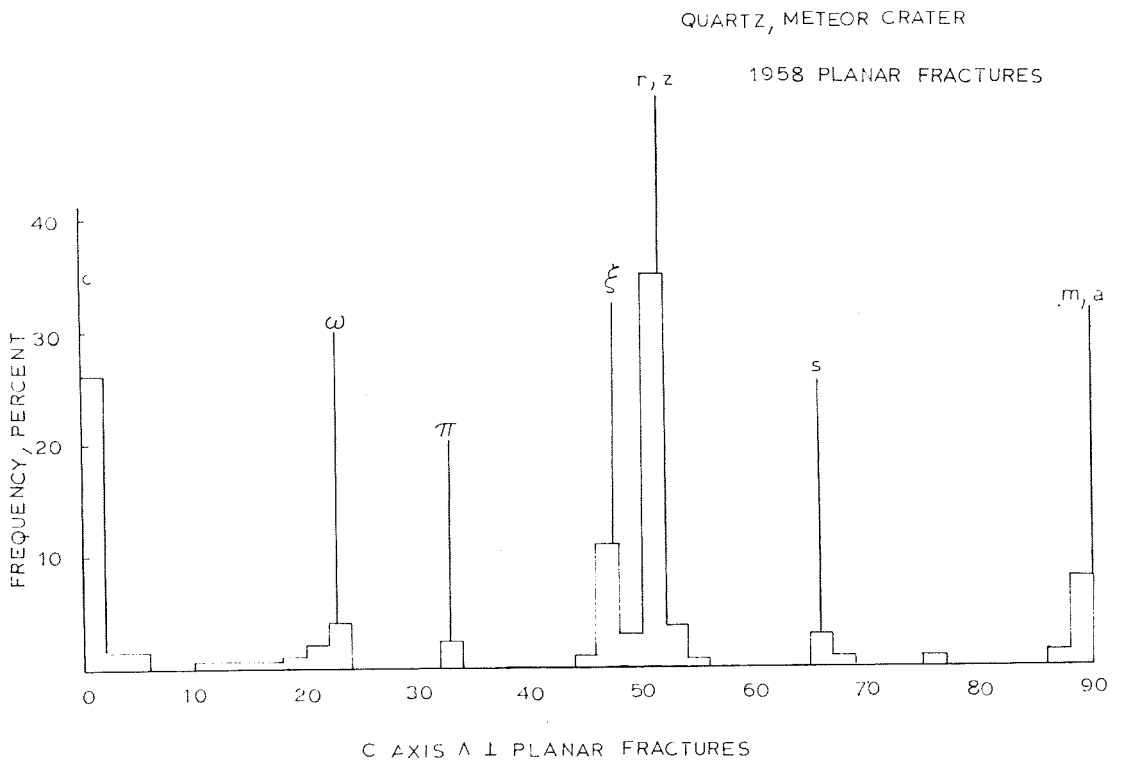

Fig. 2. Histogram showing frequency and orientation of cleavage fractures in 1958 quartz grains from Meteor Crater, Arizona.

plane were found but are statistically subordinate. From the samples of shocked Coconino Sandstone that were studied, it seems apparent that the behavior of the cleaved quartz during deformation remained elastic until rupture occurred.

Deformation of quartz specimens from Meteor Crater, Arizona and Kentland, Indiana and in a few specimens from Clearwater Lakes and Holleford may be attributed to brittle fracturing along crystallographic planes and to slight plastic flow. The fracturing of rock material during the tensional phase of the passing shock wave would favor extensive cleavage development in quartz. Initiation of a fracture along a cleavage direction probably originates at some pre-existing weakness or microcrack where there is little cohesive strength, and the quartz can be more easily pulled apart by tensile stresses.

Quartz from the Sedan Nuclear Crater, intimately associated with maskelynite, shock-disordered quartz (Bunch, Cohen, and Dence, *this vol.*, p. 509), planar features, and highly-kinked mica, contains several sets of fractures (cleavage) parallel to r and z, c, ξ, s, x, ω and π. Thus, in a single sample from the Sedan Crater, as in some highly shocked samples from the Ries, Meteor Crater, and Clearwater Lakes, a range of deformation textures can be found, ranging from lightly shocked to intensely shocked. (See Chao, 1966 for a qualitative petrographic classification of shocked rocks).

B. Basal Deformation Lamellae

There are at least three types of lamellar features in deformed quartz: Böhm lamellae, planar features, and deformation lamellae. Deformation lamellae are distinctly different from other lamellar features in that they are permanent strain zones that originate by active slip. An extensive literature exists on the occurrence of lamellar features, but only recently has there

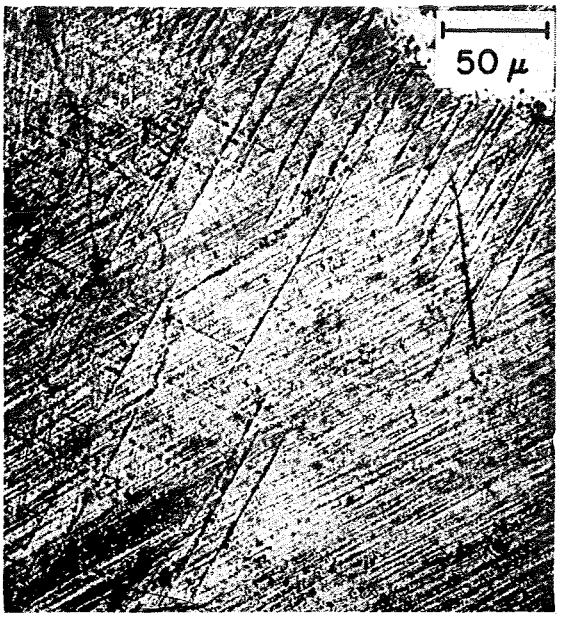

Fig. 3. Photomicrograph of "decorated" planar features in quartz from Holleford. Plane-polarized light.

been adequate experimental evidence to explain how deformation lamellae originate. These lamellae represent slip systems associated with crystallographic planes that have undergone high shearing stresses (Christie, Griggs, and Carter, 1964).

Deformation lamellae are common in quartz from most tectonic environments; however, only in meteorite craters have deformation lamellae oriented parallel to the basal plane (0001) been observed. Carter (1965) reported the discovery of basal deformation lamellae in quartz specimens from Vredefort, Meteor Crater, and Clearwater Lakes. The findings presented in this report confirm Carter's discoveries of basal deformation lamellae in quartz from these three geologic structures. Basal deformation lamellae in quartz have also been found by the writer in the Middlesboro structure, Kentucky.

Quartz grains in samples from Clearwater Lakes and Vredefort samples vary in type of microstructures present and in the extent of deformation. Basal lamellae were observed in quartz grains that also contained other microstructures, for example, planar features. Quartz sandstone from the Lee Formation of the Middlesboro structure contains basal lamellae, although it is difficult to discern most of the microstructures other than fracture because of impurity decoration or recrystallization. The optical characteristics of these basal deformation lamellae are very similar to those described by Carter (1965). (See also Robertson *et al.*, *this vol.*, p. 433; Carter, *this vol.*, p. 453.)

C. Planar Features

Other lamellar features, referred to in this report as planar features, are common in quartz deformed at ordinary strain rates. The significant difference between planar features in quartz from explosion craters and from quartz deformed at ordinary strain rates are the orientation of the planar features and the multiplicity of features (two or more sets per grain) in quartz from explosion craters.

Examination of planar features on the universal stage reveals that they are commonly regular and very narrow, but not as narrow as deformation lamellae. From simple observation at high magnifications, no definite conclusions can be made as to whether the planar features are in fact modified deformation lamellae. Most of the planar features may have apparently been fractures at some time in their history, but none of them are separated now. Under phase contrast illumination the planar features do not appear asymmetrical nor is any photoelastic effect present (Fig. 3). The planar features commonly occur as multiple sets; as many as seven different sets have been observed in one grain.

The orientation of planar features with respect to the crystallography of quartz was determined in terms of general forms but not in terms of the specific forms. Orientation data for planar features in quartz are shown in Figure 4. A large percentage of poles to planar features in quartz from Clearwater Lake have a tendency to cluster about the ω girdle (Fig. 4b). This is also true to a lesser extent for deformed quartz from Manson, Middlesboro, and Holleford. Other crystallographic planes indicated from the orientation data are π, ξ, c, r, and z. The large number of planar features parallel to c in Middlesboro quartz (Fig. 4c) also include basal deformation

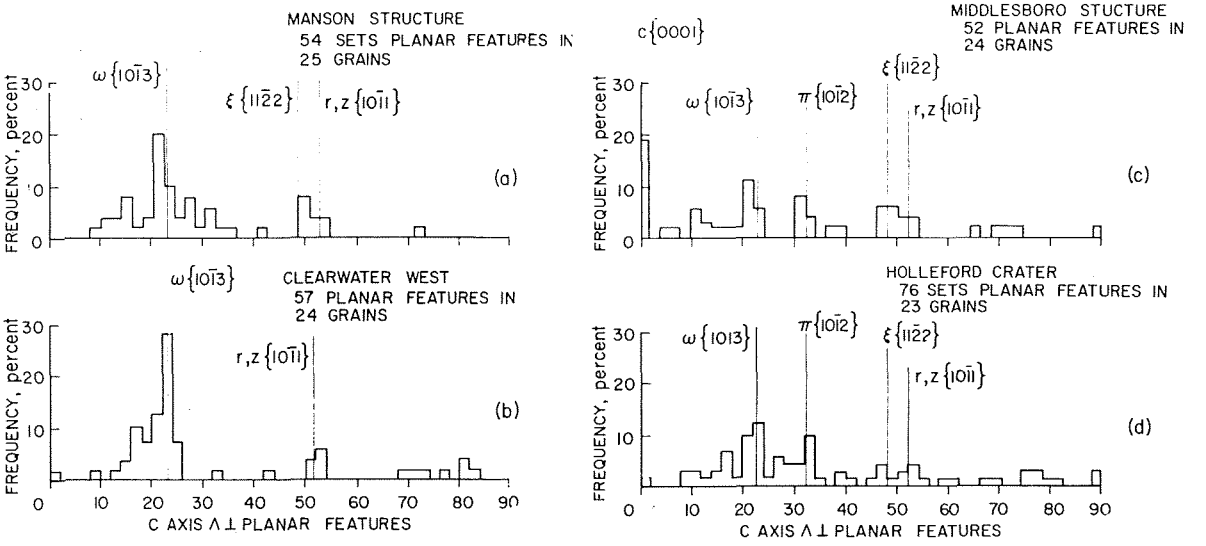

Fig. 4. Histograms showing the orientation with respect to the *c*-axis of planar features in quartz, from several cryptoexplosion structures. (a) Manson, Iowa; (b) Clearwater Lake, Quebec; (c) Middlesboro, Kentucky; (d) Holleford, Quebec.

lamellae. For comparison, composite data for lamellae and/or planar features in quartz from normal geologic environments are shown in Figure 5.

The occurrence of two or more sets of planar features in quartz grains appears to be unique to impact sites. Of all the grains studied, 68 percent have two or more sets of planar features. Engelhardt and Stöffler (1965) reported multiple planar features in shocked quartz from the Ries basin, Germany. Short (1966) has also observed similar structures in quartz from the Hardhat underground nuclear explosion and has also produced them in controlled shock implosion experiments. (Short, *this vol.*, p. 219.) Orientation data for shock imploded quartz (300 kb maximum peak pressures) are shown in Figure 6. A concentration of poles to planar features again tends to cluster about the ω girdle, but the maximum in the histogram does not coincide exactly with ω. This disparity may be accounted for by the fact that the experimentally produced microstructures are so numerous and overlapping that accurate orientation of individual planar features is very difficult (Fig. 7).

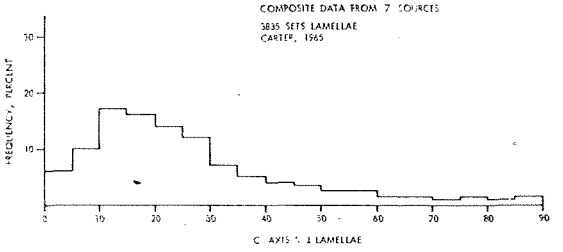

Fig. 5. Orientation data for deformation lamellae in quartz from tectonic rocks, composite data from 7 sources (Carter, 1965).

D. Deformation Bands and Kink Bands

Christie, Griggs, and Carter (1964) have pointed out the inconsistency of the use of the terms *deformation band* and *kink band* in the literature on crystal deformation. Most of the terminology and theoretical background for crystal deformation are borrowed from the science of metallurgy and their strict applications to deformation of silicate systems must be modified. In the discussion that follows, all lamellar structures in the form of bands are referred to as *deformation bands*; *kink bands* are subparallel to the *c*-axis where the slip direction lies at right angles to the intersection of the slip plane and the kink band boundary.

Deformation bands in quartz from meteorite

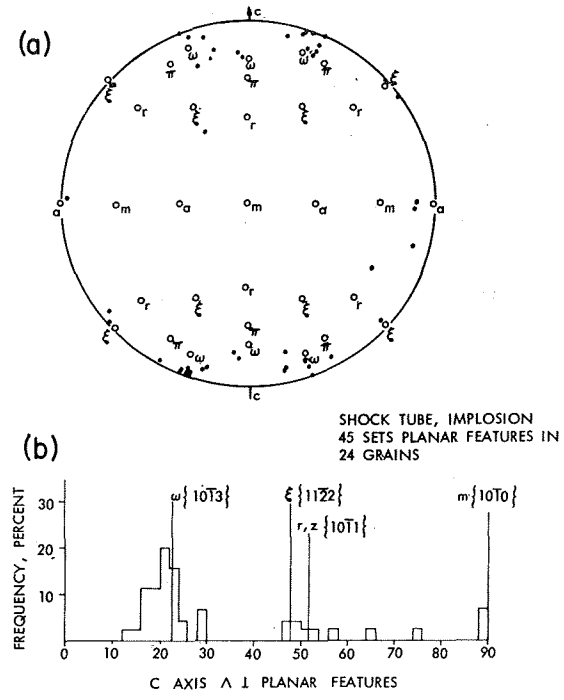

Fig. 6. Orientation data for planar features in quartz from shock tube experiments (250–300 kb). (*Specimens courtesy of N. M. Short*). (a). Orientation, with respect to the crystallography of quartz, of poles to planar features (solid circles). Equal-area projection, lower hemisphere. (b) Histogram showing the orientation with respect to the *c*-axis of planar features in artificially shocked quartz.

impact sites and from cryptoexplosion structures vary considerably in appearance. Boundaries are commonly sharp and planar and can be measured with good accuracy on the universal stage. The optical orientation within band boundaries is distinct from the host material; a few bands grade into zones of undulatory extinction. Christie, Griggs, and Carter (1964) found, by experimental deformation, that well-defined bands are prevalent in quartz crystals deformed above 500°C, while undulatory extinction or poorly defined bands are common in crystals deformed below 500°C.

Quartz in specimen C-152 from the Manson structure contains many well-defined multiple kink bands. A large single kink band is shown in Figure 8. Poles to planar features (solid circles) and *c*-axes in both the host portion and the kink band were plotted on an equal area net (Fig. 9). The *c*-axis X_B in the kink band has rotated ~27° with respect to the host grain *c*-axis. Two sets of ω planar features and one set of π planar features are present in the host and in the kink band; the amount of rotation of planar features in the kink band from planar features in the host is 24–28°.

An unusual array of multiple kink bands occurs in a breccia sample (C-286b) from Clearwater Lakes West (Fig. 10). Poles to planar features in the kink bands and in the host material, kink band boundaries, and *c*-axes are shown in Figure 11. Planar features in the host material correspond very closely to ω and π. Each kink band contains two sets of π planar features that bend sharply at the band boundaries. The amount of rotation of the *c*-axes in each band is 6° with respect to its neighbor band. Kink boundaries are inclined 12° from their respective *c*-axis.

A study of all kink bands in quartz from Manson and Clearwater Lakes specimens shows

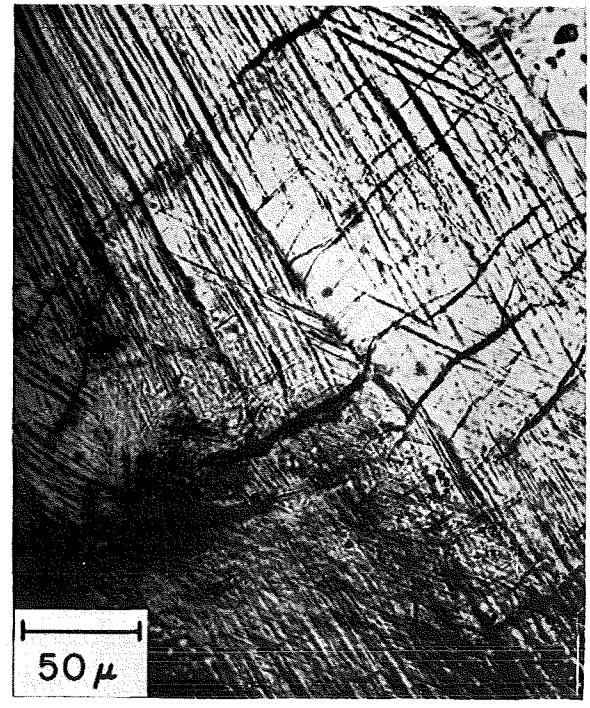

Fig. 7. Photomicrograph of quartz from the Sedan Nuclear Crater showing a high density of planar features. Plane-polarized light.

that the majority of planar features are parallel to ω with a lesser number parallel to π (Fig. 12). Kink band boundaries show a strong preferred orientation between 10°–16° from the *c*-axis. These results differ somewhat from those given by Carter, *et al.* (1964) on experimentally developed kink bands. Their kink bands vary in orientation with most of the bands oriented subparallel to the *c*-axis. The lamellae, however, form in three distinct orientations: the most common are inclined at 20°–60° to the base; and the least common are subparallel to the *c*-axis. Carter, Christie, and Griggs (1964) concluded that kink bands subparallel to the *c*-axis originate by slip on (0001) with kinking of the slip planes. This occurs only when there is high shear stress on basal planes. Lamellae and bands inclined at moderate angles (20°–60°) to the base are present in grains in which the shear stress on (0001) is low. The data presented here show no clear indication of slip on (0001). The only lamellae or planar features found in any of the kink bands are parallel to π and ω and are inclined at moderate angles to the base. The slip mechanism involved is not clearly understood; it is possible that slip does occur preferentially on these planes, but the actuality of this must be demonstrated by controlled experiments.

Fig. 8. Kink band (dark, NS-trending material) in quartz from the Manson structure, Iowa. Photomicrograph, crossed nicols.

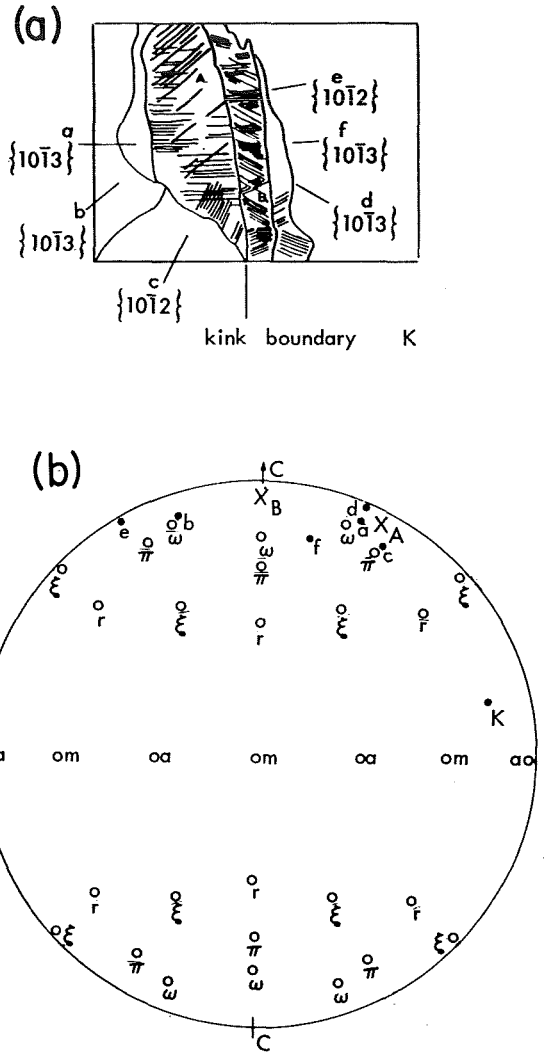

Fig. 9. (a). Sketch of quartz grain in Figure 8, showing position and orientation of planar features. A = host material, B = kink band. (b) Orientation, with respect to the crystallography of quartz, of planar features *a*, *b*, *c*, *d*, *e*, *f*, (solid circles), *c*-axis of host material X_A, *c*-axis of kink band X_B and kink band boundary *k*, of quartz grain shown in (a). Equal-area projection, lower hemisphere.

For the most part, deformation bands found in Manson and Clearwater Lakes quartz conform to the definition of, and the criteria for, kink bands (Carter, *et al.*, 1964) and are similar to kink

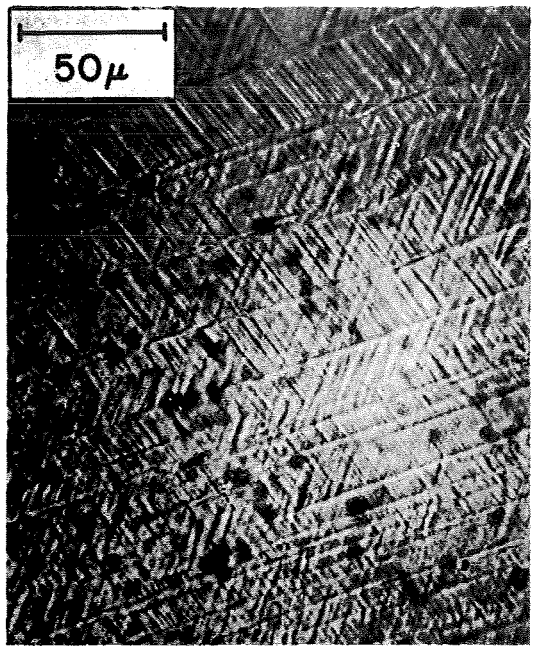

Fig. 10. Unusual array of multiple kink bands (ENE–WSW tending features) with two sets of $\pi\{10\bar{1}2\}$ planar features, Clearwater Lake West, Quebec. Photomicrograph, plane-polarized light.

bands produced experimentally for the following reasons: (a) kink band boundaries have nearly the same orientation with respect to the *c*-axis as those produced experimentally; (b) planar features form high angles to band boundaries; (c) planar features or lamellae are more closely spaced in the more highly deformed parts of the kink bands; (d) the kink bands grade into zones of bending and undulatory extinction; (e) kink band boundaries are sharp and contain many microstructures; (f) kink band boundaries are subparallel to the *c*-axis (10°–16°); (g) the axis of external rotation lies in the slip plane normal to the slip direction.

E. Discussion

The extensive development of complex cleavage in quartz is very unusual, if not unknown, in naturally deformed quartz exclusive of meteorite impact sites. Very little experimental work has been done on the stress required for the development of cleavage in quartz. Carter (1965) suggests that less stress is required to promote cleavage in quartz than is required to initiate basal slip. Wackerle (1962) studied the shock wave compression of quartz and found that deformation was not characterized by plastic flow but by complete collapse (crushing) of the structure at the dynamic yield point. He found that the Hugoniot elastic limit for samples oriented perpendicular to the *a*-axis changes from 35 kb to 50 kb; the same limit of samples oriented perpendicular to the *c*-axis changes from 65 kb to 80 kb. Collapse of the quartz structure by fracturing, with no significant change in original grain shape is a common characteristic of quartz from Meteor Crater and Wabar (Bunch and Cohen, 1964) and of several specimens from Clearwater Lakes and the Ries.

Brittle fracture is largely strain rate sensitive, but it is also dependent on temperature at the time of deformation. Very little can be said here about the quantitative values of strain rates, but from experimental results and observations it has been learned that the rate of loading plays an important part in the manner in which a material behaves during deformation. When a pressure far higher than the yield strength of a

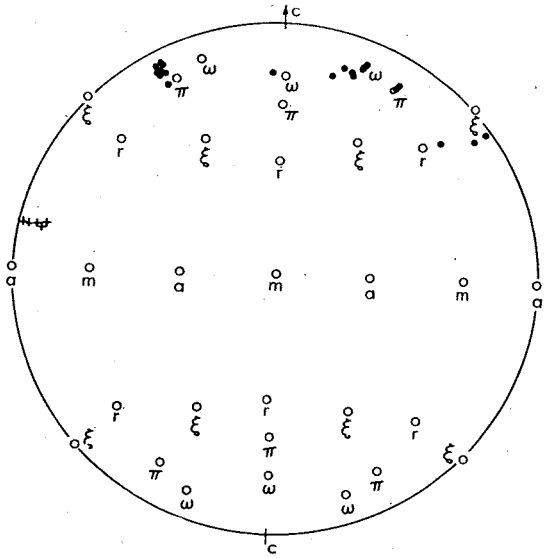

Fig. 11. Orientation, with respect to the crystallography of quartz, of poles to planar features in kink bands and host material (solid circles) and kink band boundaries (crosses) in quartz shown in Figure 10. Equal-area projection, lower hemisphere.

material is imposed abruptly, the behavior is unlike ordinary deformation. A transition from ductile to brittle fracture is observed in most materials when either the temperature is decreased during deformation or the strain rate is increased. Experimental deformation at low temperatures and high static pressures (27-30 kb) causes brittle failure in quartz (Christie, Heard, and La Mori, 1964). At higher temperatures quartz is more easily affected by plastic deformation. Cleaved quartz from Meteor Crater and Wabar is associated with coesite (and stishovite in Coconino Sandstone). Apparently the temperatures during shock were not high, or plastic flow would have replaced fracture as the dominant mode of failure. Ahrens and Gregson (1964) calculated the temperatures of several shock pressures for various sandstones to be 229°C at 25.4 kb, 336°C at 52.8 kb, 720°C at 104.5 kb and 1452°C at 190 kb. Coesite and stishovite could conceivably form with brittle fracturing of quartz at temperatures below which quartz starts to yield plastically (800°C). The minimum pressure for stishovite formation is somewhat less than 100 kb (Sclar *et al.*, 1962).

The presence of basal deformation lamellae in quartz indicates a very high stress level during deformation. Carter (1965) has calculated the stress required to initiate basal slip (deformation lamellae) in quartz from static tests to be 35 kb at 1500°C. Because of the very high stress necessary to promote slip on the basal plane, Carter (1965) concludes that basal deformation lamellae in quartz from explosion craters could only have been produced by shock waves from the impact of an extraterrestrial body.

Multiple sets of planar features in quartz were found in nearly all the structures investigated. Whether they are deformation lamellae or cleavage fractures is difficult to determine. They may be deformation lamellae that have been relieved of permanent strain by post-deformation unloading. Planar features, regardless of their origin, appear to have their own intrinsic properties and have thus far not been observed in static experiments on quartz or in quartz from other natural occurrences (Carter, 1965). They have been produced by dynamic loading and might constitute a useful criterion for recognition

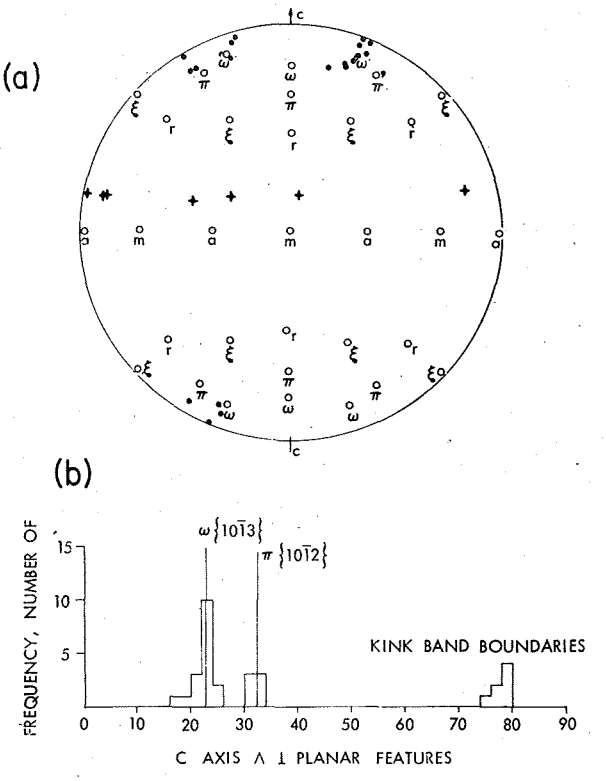

Fig. 12. Orientation data for planar features and kink band boundaries in quartz from the Manson and Clearwater Lakes West structures. (a). Orientation, with respect to the crystallography of quartz, of poles to planar features (solid circles) and kink band boundaries (crosses). (b). Histogram showing the orientation with respect to the *c*-axis of planar features in kinked quartz.

of meteorite impact sites. This suggestion is supported by other workers (Engelhardt and Stöffler, 1965; Short, 1965).

The numerous kink bands found in Manson and Clearwater Lakes quartz do not necessarily indicate shock pressure environments but they do represent unusual and complex slip features rarely found in quartz from other geologic structures.

DEFORMATION TEXTURES AND OPTICAL PROPERTIES OF ALKALI AND PLAGIOCLASE FELDSPARS

Feldspars are the second most abundant mineral found in the explosion craters investi-

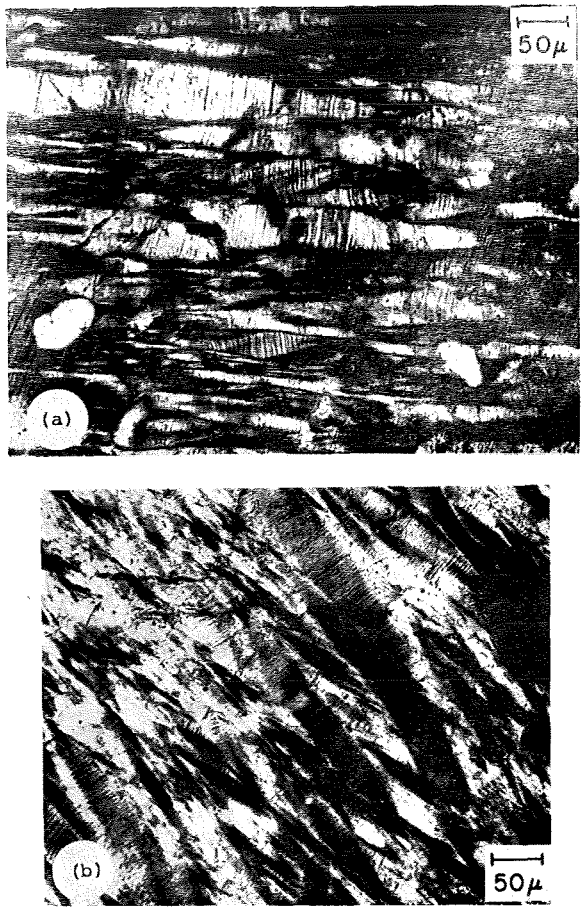

Fig. 13. (a). Photomicrograph of deformation bands (E-W-trending) in alkali feldspars from Lac Couture Crater. Deformation lamellae or planar features (N-S-trending) are also present. Crossed nicols. (b). Photomicrograph of area shown in (a) after 45° rotation of microscope stage. Crossed nicols.

gated in this report. Alkali feldspars and plagioclase associated with deformed quartz of the types described in the preceding section exhibit high degrees of strain, extensive fracturing, and deformation bands. Extensive experimental deformation studies have not been made on feldspars and no definite pressure-temperature conditions can be defined for the observed deformation textures. The following sections describe several exceptional textural characteristics of deformed feldspars found in explosion craters.

A. Alkali Feldspars

1. *Deformation Bands and Planar Features.* A characteristic feature in some of the alkali feldspar grains is the large number of lenticular deformation bands. Alkali feldspar grains from a brecciated sample of granite from Manson (C-152), polymict breccia from Lac Couture (C-270), Holleford (C-328), and Clearwater Lake West (C-286) show exceptionally well-developed bands with small contiguous kink bands. In general, the deformation bands are narrow and tend to pinch out completely or to branch into more complex strained zones. The material within the bands is optically distinct from the host material. The textures are further complicated by intense strain and by numerous planar features that greatly resemble deformation lamellae in quartz.

A large number of deformation bands with small kink bands have formed in the feldspar shown in Figure 13a. The E-W-trending bands are oriented subparallel to (010). The band boundaries are irregular and diffuse. Rotation of the microscope stage from the position shown in Figure 13a to a new position (Fig. 13b), shows the contorted nature of the bands. Planar features or deformation lamellae, the N-S-trending structures in Figure 13a, are parallel or subparallel to (001). The absence of cleavage or fracture of any kind suggests that deformation was entirely plastic.

The optic plane of the grain in Figure 13a is perpendicular to (010), indicating a monoclinic alkali feldspar. Unfortunately, the orientation of the grain in the thin section is unsuitable for measurement of the optic axial angle. The bands are multiple and complex and completely occupy all parts of the grain. Further orientation studies are hindered by the large number of small bands and by strain.

Another alkali feldspar grain in the same sample (C-270) is more suitably oriented for optical measurements (Fig. 14). Optic axial angle values in the host portion average ~60° ($2V_x$) but the material in deformation bands averages about 70° ($2V_x$). The optic plane is not perpendicular to (010), indicating that the feld-

spar is triclinic, but it is not microcline. Many of the highly strained grains appear to be triclinic or nearly so, while less strained grains tend to be monoclinic. An evaluation of slip components is difficult to derive, owing to strain and to multidirectional rotation. The band in the center (band number 7) in Figure 14 is probably a kink band. As well as can be determined, the axis of external rotation of the band lattice lies in the slip plane (lamella) normal to the slip direction. Lamellae make an angle of ~85° with the band boundary and are 90° from the rotation axis which is in the same plane. They are probably parallel to (001) but this cannot be proved. Distortion of the crystal lattice affects the optic axial angle and it is concluded that the variation of $2V_x$ values is a function of the amount of lattice distortion and not a function of variable composition. (See also Aitken and Gold, *this vol.*, p. 519.)

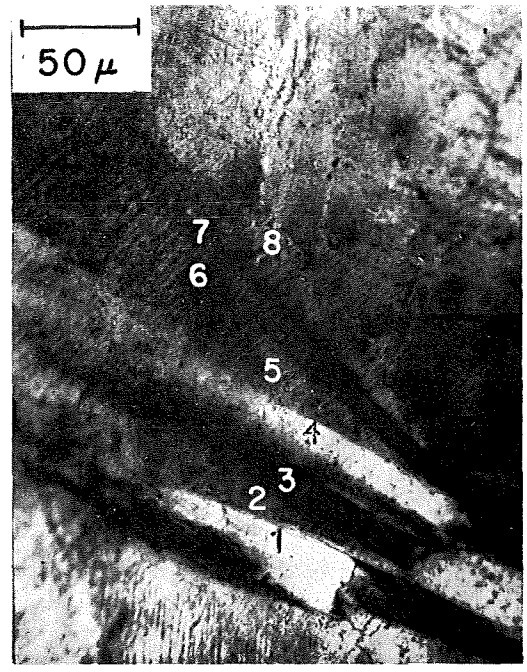

Fig. 14. Photomicrograph of deformation bands 1–6, 8 and kink band 7 in a triclinic alkali feldspar from Lac Couture. Crossed nicols.

B. Plagioclase Feldspar

(1) *Strain.* The effects of strain are very pronounced in deformed plagioclase from explosion craters. Strained crystals, on rotation of the microscope stage, do not go to extinction uniformly, owing to distortion of the crystal lattice. Strain distortion is also apparently responsible for variable optical properties, namely optic axial angles and birefringence. Measurements of optic axial angles in single deformed labradorite grains in maskelynite-bearing anorthosite from the Manicouagan structure, Quebec, show a wide range of angles. Highly strained regions with low birefringence have $2V_z$ of 60–65°; less strained regions of higher birefringence have $2V_z$ of 70°–80°. The optic axial angle for an unstrained, low-temperature (ordered) labradorite of An_{54} composition should be +74° (Slemmons, 1962). The optic sign is also variable in single grains. The acute bisectrix of several portions of individual grains changes from $Z(+)$ to $X(-)$. Deformed plagioclase from Lac Couture, Clearwater Lakes, Manson, and the Ries show similar strain effects.

(2) *Fractures.* Two types of fracturing are found in plagioclase from explosion craters: brittle, tensile-type breaks with no apparent amount of associated plastic deformation, and ductile fractures that are commonly fibrous and display a great deal of plastic deformation. Crushing and rotation of fragments have produced a cataclastic texture in some plagioclase samples. Prominent cleavage fractures parallel to (001), (010), and rarely to (110) are common in plagioclase from most of the explosion craters studied. Cleavage fractures in Manicouagan specimens are numerous and unusual. Basal (001) and (010) cleavage are well-developed in alternating bands of fractured and unfractured labradorite (An_{54}) in several grains. Ductile fractures are more common than brittle fractures and are intimately associated with deformation bands and textures, indicating plastic distortion of the crystal lattice.

(3) *Deformation Bands and Kink Bands.* Deformation bands in plagioclase are similar in appearance to those observed in alkali feldspars and are a characteristic feature of plagioclase from the Clearwater Lakes, Manson, and Lac Couture structures. Sample C-448 from Clear-

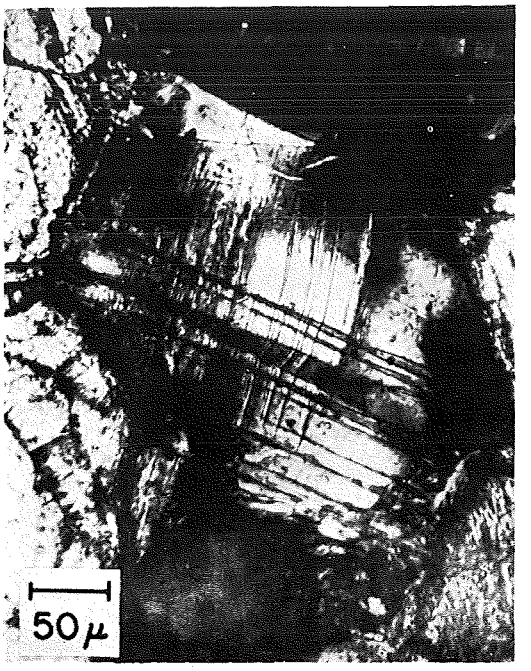

Fig. 15. Photomicrograph of kink bands in Clearwater West plagioclase (center) immediately surrounded by maskelynite, plagioclase (top center) and pyroxenes. Crossed nicols.

water Lakes contains labradorite (An_{58}) grains with kink bands associated with maskelynite (Fig. 15). The NE-trending features are slip bands parallel to (001) and are kinked across the band boundary. The optic axial angle ranges from 80° in the host to 68° ($2V_x$) in the kink band. The geometry of the kink band components indicates that the slip direction, $t=\{010\}$, lies at right angles to the intersection of the slip plane $T=(001)$, and the band boundary. The lattice within the kink band has been externally rotated 24° about the {100} zone axis.

(4) *Deformation Twinning.* The concept of deformation in plagioclase has been supported by a large body of data including work of Fedorow (1899), Harker (1939), Turner (1951), Vance (1961), Seifert (1964), and many others. Borg, *et al.* (1959) experimentally produced simple albite twins in plagioclase at 400°C and 5 kb pressure. Deformation twins are formed as the crystal yields to stress by twin gliding. The change in shape associated with deformation twinning is brought about by single shear. In an ideal case, the twin traverses the entire crystal and is different from other types of slip. Deformation by slip occurs on individual planes; in twinning, the slip is uniformly distributed over a large volume rather than a localized area. In both cases the lattice is sheared; in twinning the amount of slip is small. Vance (1961) has presented criteria for the recognition of apparent deformation twins in plagioclase.

Deformation twin lamellae are uniform in thickness but tend to pinch out abruptly if the twin ends within the grain. Plagioclase in a granite sample from Holleford core material contains a few simple deformation twins that conform to the Manebach and albite twin laws. In many of the grains with deformation twins, deformation lamellae parallel to (010) and (001) are present instead of cleavage. Irregular fractures that post-date twinning and deformation lamellae intersect and slightly offset twin lamellae. Optic axial angle ($2V_x$) measurements of plagioclase range from 84°–88° in the host to 80°–85° in the twin lamellae. The composition of the plagioclase from $2V$ values of the host is estimated to be Ab_{22}. Birefringence is lower in the host material surrounding the twins and the optic axial angle is highly variable, suggesting that lattice strain is greater in the mechanically twinned portions of the crystal.

An example of highly deformed plagioclase (Fig. 16) is from a breccia sample containing quartz with deformation lamellae and multiple planar features from Lac Couture, Quebec. The lower portion of the grain is mechanically twinned and highly strained. The complexity of deformation is made visible by continuous rotation of the microscope stage through 90° under crossed nicols from the position in Figure 16a, to the position in Figure 16d. The N-S-trending structures in Figure 16a are deformation twins (albite law) with the composition plane parallel to (010) and the twin axis ⊥ to (010). The numerous thin E-W-trending planar features are parallel to (001). Under high magnification, the material in the planar features exhibits birefringence and refractive indices lower than the host and appears to be recrystallized. Deformation bands,

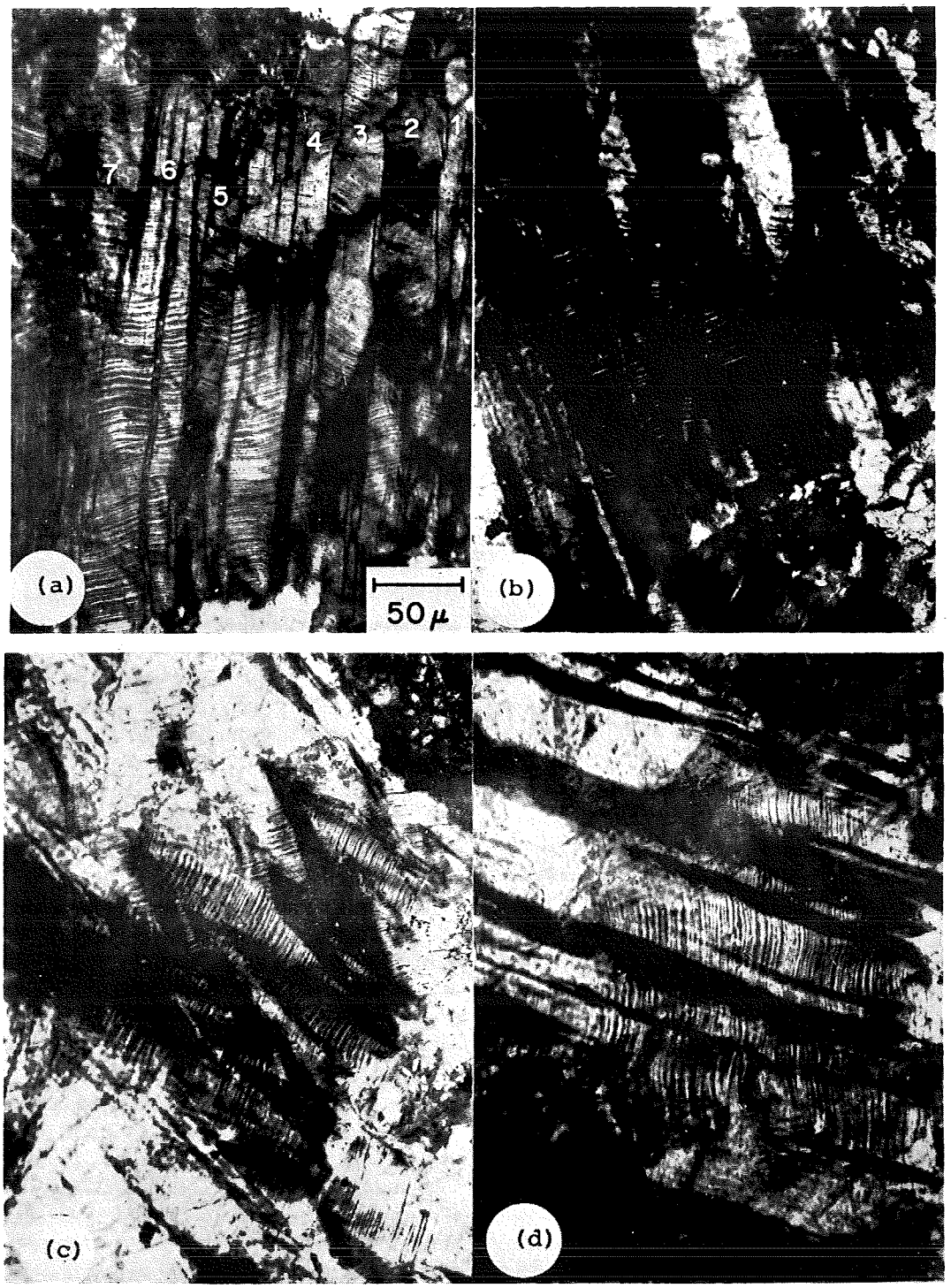

Fig. 16. (a). Photomicrograph of mechanically twinned region of plagioclase from Lac Couture, Quebec. Twins trend N-S; deformation lamellae trend E-W. Crossed Nicols. (b, c, d). Successive 30° rotations (microscope stage) from position shown in (a). Crossed Nicols.

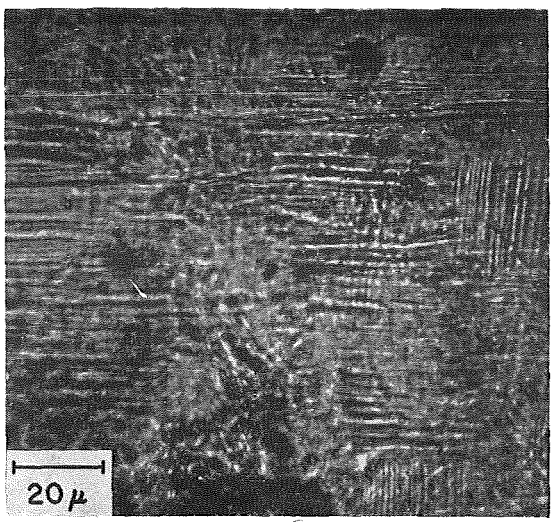

Fig. 17. Photomicrograph showing two sets of deformation lamellae oriented parallel to {100} and {001} in plagioclase. Plane-polarized light.

the chevron-like structures in Figures 16b and 16c, are inclined at low angles (20°–30°) to (010) and cause kinking of cross-trending planar features. The deformation bands are probably kink bands, but accurate measurements are unattainable because of strain and the extremely small grain size. Undulatory extinction and variation in birefringence and the optic axial angle are very evident in and near the twinned regions of the grain ($2V_x = 70°–76°$). Strain effects are less pronounced in areas away from the twinned regions ($2V_x = 76°–82°$).

5. *Deformation Lamellae and Planar Features.* Deformation lamellae parallel to (010) and (001) occur in deformed plagioclase and are similar in appearance to deformation lamellae in quartz. The lamellae are also parallel to several unresolved crystallographic planes of plagioclase. Primary albite twins in plagioclase from a Holleford specimen appear to be step-faulted. Examination under high magnification (Fig. 17) shows that the twins are offset by slip (deformation lamellae) on two different crystallographic planes. These lamellae are very narrow and are difficult to orient properly, but from the orientation data available it is possible that one set of lamellae is parallel to {100} and the other set is parallel to {001}.

Several plagioclase grains contain planar features that do not fit the criteria for deformation lamellae, but are parallel or subparallel to crystallographic planes in plagioclase. (See also Robertson *et al., this vol.*, p. 433.)

C. Discussion

The development of deformation bands in feldspars is uncommon in rocks subjected to ordinary geologic strain rates and very few examples have been reported. Seifert (1965) described deformation bands in pegmatitic albite where the deformation was only partially plastic, and Sen (1956) reported multiple translation gliding and bend gliding (deformation bands) in deformed plagioclase from a norite body. Other reported deformation bands are limited in number and are very vague as to the glide mechanisms. Deformation bands and, to a lesser extent, kink bands are numerous in deformed feldspars from explosion craters. Slip planes parallel to (001) are bent or kinked across band boundaries that are commonly subparallel to (010); however, the slip mechanism is not restricted to one set of slip planes. Secondary slip planes are present but have not been determined due to the extreme complexity of deformation effects.

The development of deformation bands and kink bands involves rotation of the crystal lattice. Complex and secondary bands (described above) are related to geometric conditions of deformation, rate of loading, temperature, and impurity content. Bands consisting of several regions rotated with respect to each other are formed in response to applied stress (compressive); the number of bands and rotation angle of the lattice within the band increases with the degree of deformation (Urusovskaya, 1962). The occurrence of such reoriented lattice regions as the result of compression is favored by rapid deformation. In metals, secondary slip or formation of "accommodation bands" results from local stresses initiated by the formation of the original deformation band or deformation twin (Urusovskaya, 1962). Evidence of secondary slip was observed in most of the examples of deformation and kink bands in feldspar from explosion craters. As stated above, accurate determination of slip directions, slip planes, and rotation axes is impeded

by the complexity of deformation. If the deformation bands shown in Figure 13a formed in response to the initially applied stresses, then these primary bands probably forced the surrounding regions to accommodate themselves by secondary slip (contiguous bands shown in Fig. 13b). Secondary slip, once initiated, would probably involve partial rotation or rearrangement of the primary bands, since the lattice has now been rotated into a favorable position for activating secondary slip, but the primary bands would now be in an unfavorable position for further slip. Several of the bands that have been designated as deformation bands because of their nonconformity to the kink band definition may actually have been kink bands that were disturbed by secondary slip.

The temperatures involved during formation of most of the deformation bands and kink bands were probably high enough to allow for complete plastic deformation (absence of fracturing).

In general, deformation twinning is caused by a special type of structural shear during plastic deformation. Crystallographic directions with lowest energy barriers are highly favorable to twinning. Deformation twins will form if resolved shearing stresses are sufficient to overcome the lattice energy barriers (Seifert, 1964). Fracture or slip may occur if the energy barriers are large, or if a large number of dislocations have built up along the prospective twin plane. Deformation twins described here are not commonly polysynthetic, nor do they have much regularity, a fact that sets them apart from other deformation twins.

Grains containing deformation twins are commonly distorted and show a heterogeneous distribution of lattice strain. Grains that contain only a few random twins have deformation lamellae present in the more strained regions; deformation twins occur in less strained regions. Apparently, deformation lamellae have formed where the directed stress was sufficient to promote extensive slip; twins formed in regions that received less stress.

Deformation or kink bands shown in Figure 16 are partially analogous to "accommodation bands" that form in metals next to twin layers. These secondary bands form by slip in response to localized stresses from mechanical twinning. Planar features in the plagioclase grains are concentrated in this region and probably represent microscopic slip traces.

In summary, the common occurrence in explosion craters of complex deformation bands, kink bands, strain-induced triclinicity in alkali feldspars, deformation twins with secondary slip, deformation lamellae, multiple planar features, and fractures in feldspars, all of which are associated with unique shock-produced microstructures in quartz, suggest a high stress level rarely observed in rocks from tectonites.

MICA

The occurrence of kink bands in deformed mica crystals from the Ries, Clearwater Lakes, Holleford, and Manson structures and from the Sedan Nuclear Crater is very common. The plane of kinking is steeply inclined to {001} cleavage and is commonly curved rather than planar. Kink bands are numerous in individual mica grains and several grains contain two conjugate sets of kinks. Similar kinks have been produced artifically in biotite of experimentally deformed granite at 500°C and 5 kb (Griggs *et al.*, 1960). Kink bands in biotite are also found in highly stressed tectonites.

Biotite in a partially fused biotite schist from the Ries (sample C-221) has numerous kink bands (Fig. 18). Kink band boundaries are steeply inclined (60°–85°) to the {001} cleavage. The amount of rotation of {001} cleavage in adjacent bands averages 38°. The *X* vibration direction lies in the plane of the thin section and is nearly perpendicular to {001} poles in the general direction of the poles to {001} cleavage illustrated in Figure 18a. Grains oriented with {001} poles at high angles to {001} poles of the grain in Figure 18a show poorly developed kink bands or are devoid of kink bands entirely (Fig. 18b).

A shocked sample of Climax granite from the Sedan Nuclear Crater contains cleaved quartz with numerous planar features, maskelynite, and "disordered" quartz as products of shock deformation (Bunch, Cohen, and Dence, *this vol.*, p. 509). Short (personal communication, July 1965) estimated the peak shock pressures on this

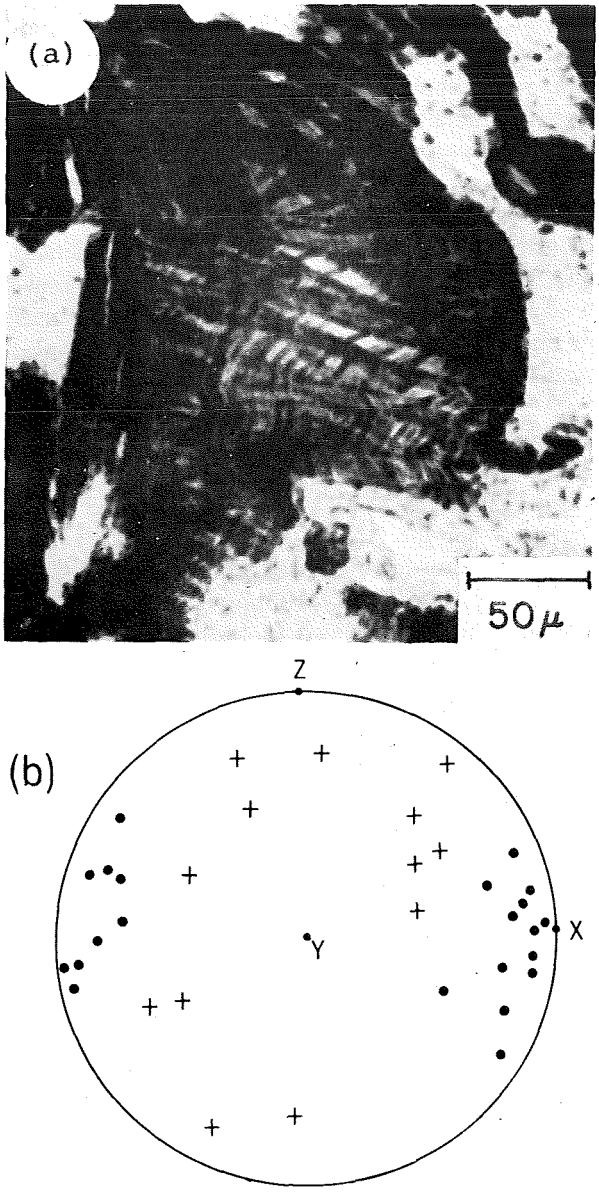

Fig. 18. (a). Photomicrograph of kink bands in Ries of Nördlingen biotite. Plane-polarized light. (b). Stereographic projection of poles to {001} cleavage in grains with poorly developed or no kink bands (crosses). Solid circles indicate poles to the {001} cleavage of biotite grains with well-developed kink bands. *X, Y, Z* represent indicatrix orientation of the reference grain shown in Figure 18a.

sample to be greater than 200 kb and less than 300 kb. The sample also contains biotite with numerous, well-defined, kink bands. The differences between these kink bands and kink bands in biotite from other localities are the number of bands per grain and their tendency to be parallel to each other. Kink bands form high angles to {001} cleavage. The biotite grains appear to have a random orientation, but there are too few grains available for good statistical orientation data.

Previous experimental work by Griggs *et al.* (1960) suggests that kink bands tend to form preferentially in grains whose {001} axes are steeply inclined to the compression axes. Turner (1964) noted, in a study of kink bands in micas of the Innsbruck mica schist, that there was a strong preferred orientation of {001} cleavage in kinked micas contrasted with non-kinked micas in response to a direction of maximum stress. Cummings (1965), in a study of shock-deformed biotite from the Hardhat event, found no relation between formation of kink bands and the direction of crystallographic axes of biotite to the direction of shock wave propagation. Rather, kink bands in biotite were formed with little regard to crystallographic orientation. Apparently, there is a wide disparity between intense shock loading and static loading on the behavior of kink band formation. With this in mind, a search was made in Sedan samples for biotite grains without kink bands. A total of 39 biotite grains from three mutually perpendicular thin sections were studied. All biotite grains were found to contain kink bands; however, large differences were observed in the number of bands, their mutual orientation within each grain, and their angular relationship with {001} cleavage.

Micas with kink bands in the Manson and Clearwater Lakes structures occur largely in fragmental breccias; measurement of fabric elements or other statistical work is meaningless. It is noted, however, that kink bands in mica from these structures are similar in orientation with respect to the crystal lattice (high angles to {001} cleavage) and in their multiplicity of individual grains.

In summary, the presence of kink bands in micas does not necessarily imply shock deformation. Kink bands are known to form under static loading conditions, both in nature and in laboratory experiments. The formation of kink bands in response to shock pressures, and the absence of any other significant deformation feature in mica does suggest that kink bands can form over a wide range of pressures and are the major mode

of failure in mica, regardless of the loading conditions. From this viewpoint, one would not expect to observe unique deformation structures in shocked micas.

In support of Cummings' (1965) conclusions, highly shocked biotite (Sedan Crater) developed kink bands with little regard to crystallographic control; it seems reasonable to assume that crystallographic control of kink bands is valid only under pressure environments of much lower strain rates than impulsive loading.

SUMMARY AND CONCLUSIONS

Most of the constituent minerals of rocks from near the centers of the structures studied in this investigation show significant differences in mode of failure when compared with minerals from other tectonic environments. Quartz commonly shows a high degree of cleavage development and numerous basal deformation lamellae; both microstructures result from high pressures possibly coupled with high strain rates. Multiple sets of planar features, including the rare morphological forms $\{10\bar{1}2\}$ and $\{10\bar{1}3\}$, appear to be unique to quartz from explosion craters. Numerous deformation bands, complex deformation twins, brittle fractures, deformation lamellae, and kink bands are found in feldspars. Pronounced strain in feldspars greatly affects the optic axial angle. No correlation has been found between the refractive index of shock deformed plagioclase and the empirical $2V$ values of high temperature and low temperature plagioclase. Kink bands in biotite form over a wide range of pressures (several hundred bars of directed pressure to several hundred kilobars of shock pressures).

On the basis of previous work by other investigators and the petrographic observations reported here, applying the petrographic classification of Chao (1966), Meteor Crater, Clearwater Lakes, the Ries, and Holleford, are considered by the writer to have been formed by strong shock associated with meteorite impact. The explosion craters Lac Couture, Manson, Middlesboro, and Vredefort show evidence of violent disruption and contain numerous unusual microstructures, but rocks containing shock-formed glasses and/or high pressure silica polymorphs have not been found and the origin of these craters can at present only tentatively be ascribed to meteorite impact.

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REFERENCES

Ahrens, T. J., and V. G. Gregson, Shock compression of crystal rocks: data for quartz, calcite, and plagioclase rocks, *J. Geophys. Res., 69*, 4839–4874, 1964.

Aitken, F. K., and D. P. Gold, The structural state of potash feldspar: a possible criterion for meteorite impact?, *this vol.*, p. 519.

Boon, J. D., and C. C. Albritton, Jr., Meteorite craters and their possible relationships to "cryptovolcanic structures". *Field and Lab. 5*, 1–9, 1936.

Borg, I., J. Handin, and D. V. Higgs, Experimental deformation of plagioclase (abs.). *J. Geophys. Res., 64*, 1094, 1959.

Bucher, W. H., Cryptovolcanic structures in the United States. *Internat. Geol. Congr., 16th, United States, 1933, Reports 2*, 1055–1084, 1936.

Bucher, W. H., Cryptoexplosion structures caused from without or from within the earth? (astroblemes or geoblemes?). *Am. J. Sci. 261*, 597–649, 1963.

Bunch, T. E., and A. J. Cohen, Coesite and shocked quartz from Holleford Crater, Ontario, Canada, *Science, 142*, 379–381, . 963.

Bunch, T. E., and A. J. Cohen, Shock deformation of quartz from two meteorite craters, *Bull. Geol. Soc. Am., 75*, 1263–1266, 1964.

Bunch, T. E., A. J. Cohen, and M. R. Dence, Shock-induced structural disorder in plagioclase and quartz, *this vol.*, p. 509.

Carter, N. L., Basal quartz deformation lamellae—a criterion for recognition of impactities, *Am. J. Sci., 263*, 786–806, 1965.

Carter, N. L., Dynamic deformation of quartz, *this vol.*, p. 453.

Carter, N. L., J. M. Christie, and D. T. Griggs, Experimental deformation and recrystallization of quartz. *J. Geol., 72,* 687–733, 1964.

Chao, E. C. T., Impact metamorphism. *U.S. Geol. Survey Astrogeol. Studies Ann. Prog. Rep., Part B, July 1, 1965 to July 1, 1966,* 135–169, 1966.

Chao, E. C. T., J. J. Fahey, J. Littler, and D. J. Milton, Stishovite, SiO_2, a very high-pressure new mineral from Meteor Crater, Arizona, *J. Geophys. Res., 67,* 419–421, 1962.

Chao, E. C. T., and J. Littler, Additional evidence for the impact origin of the Ries Basin, Bavaria, Germany (Abs.), *Geol. Soc. Am. Spec. Paper 73,* 127, 1963.

Chao, E. C. T., E. M. Shoemaker, and B. M. Madsen, First natural occurrence of coesite. *Science, 132,* 220–222, 1961.

Christie, J. M., D. T. Griggs, and N. L. Carter, Experimental evidence of basal slip quartz. *J. Geol. 72,* 734–755, 1964.

Christie, J. M., H. C. Heard, and P. N. La Mori, Experimental deformation of quartz single crystals at 27–30 kb confining pressure and 24°C, *Am. J. Sci., 262,* 26–55, 1964.

Coes, L., A new dense crystalline silica. *Science, 118,* 131–132, 1953.

Cummings, D., Kink bands: shock deformation of biotite resulting from a nuclear explosion, *Science, 148,* 950–952, 1965.

Dietz, R. S., Meteorite impact suggested by the orientation of shatter cones at the Kentland, Indiana disturbance. *Science, 105,* 42–43, 1947.

Dietz, R. S., Shatter cones in cryptoexplosion structures (meteorite impact?). *J. Geol., 67,* 496–505, 1959.

Dietz, R. S., Meteorite Impact suggested by shatter cones in rock. *Science, 131,* 1781, 1960.

Dietz, R. S., Cryptoexplosion structures: a discussion. *Am. J. Sci., 261,* 650–665, 1963.

Duvall, G., Shock waves in solids, *Internat. Sci. and Technol., 16,* 45–54, 1963.

Engelhardt, W. v., and D. Stöffler, Spaltflächen im Quartz als anzeichen fur Einschläge grosser Meteoriten. *Naturwiss., 52,* 489–490, 1965.

Fedorow, E., Biegungsaxe der Feldspath. *Mineral. Petrol., Mitt., 18,* 360–366, 1899.

Gilbert, G. K., The moon's face: a study of the origin of its features. *Bull. Phil. Soc. Wash., 12,* 241–292, 1893.

Griggs, D. T., F. J. Turner, and H. C. Heard, Deformation of rocks at 500°C and 800°C., *Geol. Soc. Am. Mem. 79,* 39–104, 1960.

Harker, A., *Metamorphism,* 2nd Ed., London, Metheun, 362 p., 1939.

McIntyre, D. B., Impact metamorphism at Clearwater Lake, Quebec (Abs.), *J. Geophys. Res. 67,* 1647, 1962.

Robertson, P. B., M. R. Dence, and M. A. Vos, Deformation in rock-forming minerals from Canadian craters, *this vol.*, p. 433.

Sclar, C. B., A. P. Young, L. C. Carrison, and C. M. Schwartz, Synthesis and optical crystallography of stishovite, a very high pressure polymorph of SiO_2. *J. Geophys. Res., 67,* 4049–4054, 1962.

Seifert, K. E., The genesis of plagioclase twinning in the Nonewaug granite, *Am. Mineralogist, 49,* 297–320, 1964.

Seifert, K. E., Deformation bands in albite, *Am. Mineralogist, 50,* 1469–1472, 1965.

Sen, S., Translation gliding in deformed plagioclase from a banded norite near Willow Lake, Oregon, *Internat. Geol. Congr., 20th,* Mexico City, 263–274, 1956.

Shoemaker, E. M., and E. C. T. Chao, New evidence for the impact origin of the Ries basin, Bavaria, Germany. *J. Geophys. Res. 66,* 3371–3378, 1961.

Short, N. M., A comparison of features characteristic of nuclear explosion craters and astroblemes, *Ann. N.Y. Acad. Sci., 123,* 573–616, 1965.

Short, N. M., Effects of shock pressures from a nuclear explosion on mechanical and optical properties of granodiorite, *J. Geophys. Res., 71,* 1195–1216, 1966.

Short, N. M., Experimental microdeformation of rock materials by shock pressures from laboratory-scale impacts and explosions, *this vol.*, p. 219.

Slemmons, D. B., Determination of volcanic and plutonic plagioclases using a three of four-axis universal stage, *Geol. Soc. Am. Spec. Paper 69,* 1–37, 1962.

Stishov, S. M., and S. W. Popova, New dense polymorphic modification of silica (in Russian), *Geokhimiya, 10,* 837–839, 1961.

Turner, F. J., Observations on twinning of plagioclase in metamorphic rocks. *Am. Mineralogist, 36,* 581–589, 1951.

Turner, F. J., Analysis of kinks in mica of an Innsbruck mica schist. *Neues Jahrb. Mineralogie,* 347–356, 1964.

Turner, F. J., D. T. Griggs, and H. C. Heard, Experimental deformation of calcite crystals. *Bull. Geol. Soc. Am., 65,* 883–934, 1954.

Urusovskaya, A. A., Formation of regions with a reoriented lattice as a result of deformation of mono- and polycrystals, in *Plasticity of crystals,* Klassen-Neklyudova, Editor, pp. 67–104, New York, Consultants Bureau, 1962.

Vance, J. A., Polysynthetic twinning in plagioclase, *Am. Mineralogist, 46,* 1097–1119, 1961.

Wackerle, J., Shock-wave compression of quartz, *J. Appl. Phys. 33,* 922–937, 1962.